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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report presents a summary of the research activities, major accomplishments, publications and presentations resulting from the project supported by ONR grant N000140310324 to Auburn University. Key contribution of this project was the development and experimental testing of a variety of information displays, called "reactive information displays," that could modify the presented information in real-time in response to the viewer's gaze patterns. Designs of these displays were based on a cognitive model of multimodal information comprehension developed in a previous ONR project (N000149611187). Reactive information displays were tested in the domains of mechanics and computer science. Results showed that various display strategies for augmenting information presented based on knowledge about both the viewer's gaze patterns and the problem solving procedure he or she is employing could indeed improve problem-solving performance.

15. SUBJECT TERMS

cognitive model, empirical studies, information display design, eye tracking

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This report is structured in the same format as annual performance and progress reports. It has the same sections, and each section contains relevant cumulative information over the entire project period.

1. Personal Information

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ONR Program Officer:	Dr. Astrid Schmidt-Nielsen

2. Co-Principal Investigator

None

3. Progress Summary

3.1 Discussion of how the project results respond to the objectives of ONR

The amount of information that military decision makers and planners have to deal with and its rate of change are both increasing rapidly, as the scope and technologies of war fighting change. For instance, geographic separation between the command and control center (typically located in the US) and the actual theatre (which could be anywhere in the world), availability of continuous information on location and movements of various units, real-time weather information, and increased reliance on unmanned aerial, land and underwater reconnaissance vehicles have all necessitated both the development of information visualization techniques and the use of large information displays. An example of such display technology is the Knowledge Web/Wall project at Navy's San Diego SPAWAR Systems Center.

However, the physical size of information displays, however large, is still limited. Trying to present too much information too rapidly on a fixed size display can result in information overload, stress and poor performance on the part of the operator. One solution to this is adaptively and progressively providing information on the display while guiding the user's attention. While this seems like a common sense solution to the information overload problem, basic research that illuminates how best to serially present information, how to guide the visual attention of a problem solver on an information display, and how to provide details at the right time and right place on the display to achieve optimal performance is still lacking. Without such research, the development of display technology alone will not guarantee that human decision-makers will be able to effectively assimilate and act on the information being presented. Results from this project contributed to advancing the knowledge base on these basic research issues.

The work applied an empirically validated cognitive process model of comprehension, developed in prior ONR-supported research, to generate principled ways of adaptively presenting information to users, and measured how this affected problem-solving performance. The primary objectives of developing adaptive information presentation techniques based on a theoretical foundation, and empirically demonstrating their positive influence on human problem-solving performance, have been achieved. In particular, we:

> developed a scientific understanding through basic experimental research of how a cognitive model could be applied to adaptive information display design, and how such displays affected human problem-solving performance; and

> designed human interface technology for adaptive information displays that tailored presentations based on a set of cognitive principles and eye movements of the user.

Enhancement of human performance has been designated as one of the key overarching science and technology issues for the Navy of the future. In a technology-dependent Navy, complex information displays will be omnipresent and superior situational awareness and quick-reaction decision making will be required of personnel. Basic scientific research on how to improve information assimilation and problem solving through adaptive displays can therefore potentially influence the design of future Navy information presentation systems. Such research can also aid current projects such as the Knowledge Web/Wall. As the Navy relies more and more on remote-sensing technologies to monitor and plan operations, the corresponding information displays will rely heavily on graphical representations. Thus, the capability to collect, analyze and correlate users' gaze patterns on graphical displays to comprehension and performance measures that we developed in this project should prove useful to evaluate the efficacy of such displays. This is how this research responds to ONR's Human Interface Systems Technology objective of optimizing the interface between the operator and equipment for improved efficiency. This research matches with the program thrust on multimedia displays, visualization and presentation. It also has relevance to the thrusts on decision support and workstation interfaces.

3.2 Project tasks

The main research tasks carried out are enumerated below.

1 Theory development through experimental investigations – Further developed the theoretical foundation built during previous ONR supported research by experimentally investigating how a cognitive process model of multimodal comprehension, developed in that prior research project, could be applied to improving measurable aspects of human problem-solving performance from information displays. This was accomplished by experimentally investigating whether and to what extent human performance is affected when an information display adapts its presentation according to each of the following techniques derived from the cognitive model:

1.1 Compared performance when a user's visual attention is guided along the lines-of-action produced by causal influences, to when the display provides no such guidance.

1.2 Compared performance when the display shows local processes through visualization techniques such as animation, to when the display is static.

1.3 Compared performance when the information display is initially sparse, with detailed information being progressively revealed, to when the display presents all information simultaneously.

1.4 Compared performance when relevant background information is dynamically displayed, to when the display requires a user to explicitly look at a static presentation of background information.

2　Designed technology – algorithms and implemented software – for adaptive information displays that collects information regarding the user's gaze and applies this information, in accordance with the above techniques, to modulate information presentation in ways that improved human performance.

3　Trained graduate computer science students in cognitive and computational aspects of Human Interface Systems Technology: designing and implementing advanced interaction techniques, and designing, conducting and analyzing data from experiments with human users.

4　Dissemination – results were disseminated through publications and presentations at annual ONR PI meetings and other venues.

3.3 Description of reactive information display designs developed

1　A display that automatically highlights the next piece of information a user must attend to in order to solve a presented causal or algorithmic reasoning problem in an optimal way, in order to draw the user's attention to that information from wherever he or she is looking currently, and does this for every piece of relevant information on the display in an optimal order.

2　A display that automatically highlights the current piece of information a user is attending to, i.e., that tracks and responds to the shifts of the user's visual attention.

3　A display that automatically highlights the next piece of information a user must attend to in order to solve a presented causal or algorithmic reasoning problem in an optimal way, where this next item is dynamically selected by the system based on the last piece of information the user attended to and dwelled on for a time interval above a threshold.

4　A display that automatically highlights the next piece of information a user must attend to in order to solve a presented causal or algorithmic reasoning problem in an optimal way, where this next item is dynamically selected by the system based on the problem solving procedure the user needs to employ for optimal performance, and tracks the user's gaze to ensure that the information is attended to and dwelled on for a time interval above a threshold.

5　A display that does not react as long as the user is attending to pieces of information in an order conforming to the problem solving procedure the user needs to employ for optimal performance, but highlights the next piece of information to be attended to when it detects that the user's gaze breaks from this optimal pattern until his or her attention is drawn back to the appropriate piece of information.

6　A display that does not react as long as the user is attending to pieces of information in an order conforming to the problem solving procedure the user needs to employ for optimal performance, but highlights the next piece of information to be attended to when it detects that the user's gaze breaks from this optimal pattern until his or her attention is drawn back to the appropriate piece of information, or, if the user starts looking at a different path in the display, employs the same highlighting strategy along this new path.

7　A display that automatically animates the dynamic behavior of the next piece of information (e.g., the rotation of a mechanical component) a user must attend to in order to solve a presented causal or algorithmic reasoning problem in an optimal way, in order to draw the user's attention to that information from wherever he or she is looking currently, and does this for every piece of relevant information on the display in an optimal order.

8 A display that automatically animates the dynamic behavior of the current piece of information (e.g., the rotation of a mechanical component) a user is attending to, i.e., that tracks and responds to the shifts of the user's visual attention.

9 A display that automatically animates the dynamic behavior of the next piece of information a user must attend to in order to solve a presented causal or algorithmic reasoning problem in an optimal way, in order to draw the user's attention to that information from wherever he or she is looking currently, while additional background information is shown in a separate region of the display in a static manner.

10 A display that automatically animates the dynamic behavior of the next piece of information a user must attend to in order to solve a presented causal or algorithmic reasoning problem in an optimal way, in order to draw the user's attention to that information from wherever he or she is looking currently, while showing additional textual information close to the animated information in a dynamic fashion.

11 A display that starts out blank, then progressively reveals information, one item at a time, in the order that a user must attend to them so as to solve a presented causal or algorithmic reasoning problem in an optimal way.

3.4 Summary of experiments with reactive information displays

1 We conducted an experiment to compare hardware and software based eye-tracking methods.

2 We conducted a second experiment to investigate the strategies of successful and unsuccessful problems solvers in tasks requiring them to solve mechanical reasoning problems from diagrams.

3 We conducted a third experiment to investigate the role of mental imagery in solving mechanical reasoning problems in the presence and absence of external diagrams. One hundred and eleven engineering students participated in these experiments as subjects.

4 We conducted seven more experiments involving 355 engineering students to evaluate nine of the above described reactive information displays.

3.5 Summary of software developed

1 We developed software that labels fixations with names of objects on the display so that raw eye movement data can be reduced to a temporal series of display objects attended to.

2 We developed software that allows an experimenter to define a region of interest on a display by clicking and dragging the mouse, and then automatically computes focus shifts in and out of the region along with associated fixation times.

3 In addition to standard measures of problem solving performance such as time-on-task and accuracy, we developed two measures of how systematic a user's visual search on a display is. These are called coverage and order. Coverage is defined as the percentage of objects in the display that were attended to for more than a time interval threshold. It is a number between 0 and 100. Order is a measure of how closely a user's gaze shifts followed the optimal order of attending to various pieces of information on the display as dictated by an optimal problem solving procedure. We developed software to automatically calculate order and coverage from raw eye movement data and information

about boundaries of various display objects.

4   We developed software-based implementations of nine of the reactive information displays described above so that a computer running the display was linked to another computer controlling a head-mounted Eye Link eye tracker.

5   We combined the various pieces of eye movement data reduction and analysis software to produce an integrated eye movement data analysis tool.

6   We integrated the various reactive information display software to create a reactive information display design toolkit to make the process of prototyping and evaluating such displays easier in future.

4. Long Term Goals

Our long-term goals, beyond the end of the ONR project period, are to (1) invent, implement and evaluate additional reactive information displays that use different information adaptation strategies, (2) thereby develop a theoretical foundation for the principled design of information displays based on tracking and responding to user's attention shifts in order to improve problem solving performance, and (3) to apply our techniques to realistic decision making and problem solving scenarios in the domains of planning and emergency response.

5. Results: Best Accomplishments

1   The development of a measure of how closely a user's gaze shifts followed the optimal order of attending to various pieces of information on the display as dictated by an optimal problem solving procedure. An efficient and successful problem solver will not only attend to all relevant objects in the display, but also consider them in the order that best supports reasoning. Therefore, the metric that we developed, called "order," is one that measures how systematically a user attended to causally related elements of the display. It is defined as follows. Let S be an ordered sequence of display objects that a user attended to during a problem solving session. So S begins with the first display item attended to, and ends with the last item attended to before the solution to the problem is produced. This sequence is generated from eye movement data. In this sequence, if object j appears immediately after object i, and if i can causally influence j according to the lines of action in the system, then i-j represents a causal link in the sequence S. Consecutive causal links represent causal subsequences of S. The length of a causal subsequence is the number of causal links in it. Order of S is defined as the sum of squares of the lengths of causal subsequences in S. This captures the correctness of the order in which the user processed the display (i.e. each causal link indicates that the problem solver considered one accurate cause-effect pair of display objects) weighted by the length of lines of action that have been considered (i.e. if users A and B both considered the same number of causal links, but if A looked at longer chains of causal links than B, the value of order will be higher for A than B). Order is an integer greater than or equal to zero.

2   Experimentally demonstrated that while a hardware based eye tracker is faster and more natural to use, data accuracy is higher for a software based eye tracker operating on a "key-hole view" principle.

3   Experimentally characterized aspects of successful causal reasoning and problem solving: longer time-on-task and attending to more components of the problem do not necessarily lead to success in mechanical reasoning problems presented on graphical displays; instead, systematically searching the display with higher values of the measure order (described above) and concentrating on critical components of the problem lead to higher accuracy.

4 We did not find a significant difference in accuracy between those who employed mental imagery in solving problems of the kind described above and those who did not. However, successful problem solvers who employed mental imagery were more systematic in their allocation of visual attention, and concentrated more on critical components, than unsuccessful problem solvers who employed mental imagery.

5 We found that reactive information displays encouraged systematic visual search and improved problem solving performance. See section 8 for details.

6. Scientific and Technical Objectives

The main objectives of the research effort were to (i) develop, through basic experimental research, a cognitive approach that can inform display designers as to how information presentations may be adapted to improve human problem-solving performance, and (ii) develop and empirically evaluate several technical designs for such displays for different problem types and domains.

7. Approach

Our approach consisted of the following steps:

1. Invent approaches to adapt information displays in real time based on eye movement data and principles derived from a cognitive model of information comprehension developed in an earlier ONR project.

2. Design corresponding reactive information displays for presenting problems in the mechanical and algorithmic domains to users to solve.

3. Implement display prototypes.

4. Experimentally evaluate the displays.

5. Use the findings to develop a theory of reactive information displays.

8. Impact of Basic Research

This research made several contributions. The primary one was a theoretical framework for the principled design and evaluation of information displays that track the visual attention of users and react according to a generalized model of comprehension and problem solving. Four research questions about the impact of reactivity were raised and investigated — Is problem solving performance improved when: (1) The user's visual attention is guided along paths of causal influence? (2) Local component behaviors are animated in regions of the display, after the user's attention has been attracted to the regions? (3) The information display is initially sparse, with detailed information being progressively revealed? (4) Relevant background information is shown in regions of the display while the user attends to those regions?

To examine the efficacy of reactive information displays implementing these strategies, we measured nine dependent variables: accuracy of problem solving, post-test score, response time, coverage, number of focus shifts between critical elements of the display, number of focus shifts between all display elements, order of visual attention shifts, dwell time on critical components, and animation tracking behavior of users.

The following are our findings. Users with higher accuracy also score higher in the post-test. Users who take longer to solve a problem also tend to exhibit higher coverage, order and number of focus shifts. Reactive information displays with animations that guide a user's visual attention along causal paths increased accuracy and also increased coverage, number of focus shifts, dwell time on critical components, order (i.e. systematicity of visual search) and response time. Reactive information displays that progressively revealed information increased accuracy, order and critical component dwell time while decreasing coverage. Reactive information displays that guided a user's visual attention to the next display element according to an optimal search strategy, or followed a user's gaze patterns to detect deviation from this strategy and upon such detection highlighted relevant portions of the display to get the user back on track, improved accuracy, coverage, order of visual search, critical component dwell time and post-test scores. Reactive information displays with animations, progressive revealing and next component highlighting improved accuracy, and increased coverage, focus shifts, order, critical component dwell time, response time and post-test score. In summary, we have strong initial evidence that reactive information displays positively influence multiple aspects of a problem solver's visual search and accuracy.

This project has thus contributed to the development of a cognitive comprehension model and a principled approach to the design of information displays that adapt information presented in response to user's gaze patterns and in accordance with known optimal procedures for problem solving. These results have the potential to improve the design of large-scale information displays that military commanders and emergency response centers use to provide information in real time to decision makers and planners. The eye-tracking laboratory at Auburn is one of the very few research groups in the United States investigating the application of eye tracking to information display design. We have developed various pieces of software for making analysis of eye movements easier, and for realizing gaze-contingent displays. These technologies have mainly been used in-house for supporting basic research. Since the focus of this research project was not developing and disseminating eye tracking technology per se, the impact of the technology we have developed is indirect in terms of its support of basic research. In the longer term, we expect this software technology development effort to promote more widespread use of eye movement data collection and analysis in basic research on problem solving, planning, decision-making, etc.

9. Technology Transfer

Our main means of facilitating technology transfer has been through publications and presentations at forums attended by scientists and engineers from academia, industry and military. We have disseminated the results of our research to the cognitive psychology, human-computer interaction, multimedia and interactive system design communities. For more information, see sections 13 (publications) and 13 (presentations) below.

10. Statistics

Number of Degrees Granted: 2
PI/CoPI Minority Women**: 0
PI/CoPI Non-Minority Women: 0
PI/CoPI Minority Men**: 0
PI/CoPI Non-Minority Men: 1
Grad Students Minority Women**: 0
Grad Students Non-Minority Women: 0
Grad Students Minority Men**: 0

Grad Students Non-Minority Men: 2
Post Doctoral Minority Women**: 0
Post Doctoral Non-Minority Women: 0
Post Doctoral Minority Men**: 0
Post Doctoral Non-Minority Men: 0
Undergrad Students Minority Women**: 0
Undergrad Students Non-Minority Women: 0
Undergrad Students Minority Men**: 0
Undergrad Students Non-Minority Men: 0
Number of journal articles in preparation, revision or review: 3
Number of journal articles published: 0
Number of articles published in conference proceedings or books: 5
Number of technical and final reports authored: 2
Number of patents issued or pending: 0

11 References to publications resulting from this project

Note: Several journal publications are in various stages of preparation, revision or review. Only accepted or published articles are listed below. Copies of these papers (and any future publications arising from this project) may be downloaded from http://www.eng.auburn.edu/~naraynh/pubs.html.

1   Narayanan, N. H. (2006). Cognitively based design of expository multimedia on causal and dynamic systems. Chapter in Alamargot, Terrier & Cellier (Eds.), *The Handbook of Production, Comprehension and Use of Technical Documents at Work*, Elsevier Science Publishers, to appear.

2   Yoon, D. & Narayanan, N. H., Lee, S. & Kwon, O. (2006). Exploring the effect of animation and progressive revealing on diagrammatic problem solving, *Diagrammatic Representation & Inference: Proceedings of the Fourth International Conference on the Theory and Application of Diagrams, Lecture Notes in Artificial Intelligence*, Vol. LNAI 4045, Springer, pp. 226-240.

3   Yoon, D. & Narayanan, N. H. (2004). Mental imagery in problem solving: An eye tracking study. *Proceedings of the Third ACM Symposium on Eye Tracking Research & Applications*, Association for Computing Machinery (ACM) Press, pp. 77-83.

4   Yoon, D. & Narayanan, N. H. (2004). Predictors of success in diagrammatic problem solving. Diagrammatic Representation & Inference: *Proceedings of the Third International Conference on the Theory and Application of Diagrams, Lecture Notes in Artificial Intelligence*, Vol. LNAI 2980, Springer-Verlag, pp. 301-315.

5   Narayanan, N. H. & Yoon, D. (2003). Reactive information displays. *Proceedings of INTERACT 2003: Ninth IFIP TC 13 International Conference on Human-Computer Interaction*, IOS Press, pp. 244-251.

6   Yoon, D. & Narayanan, N. H. (2003). What separates successful and unsuccessful problem solvers in diagrammatic reasoning? Technical Report CSSE03-05, Computer Science & Software Engineering Dept., Auburn University, Auburn, AL 36849, 6 pages.

12. Honors

1. Narayanan was awarded Auburn University College of Engineering Senior Faculty Research Excellence Award in 2005, in part recognizing his research on this project.

13. Presentations

1. Invited Seminar, "Understanding and reasoning about complex systems: A cognitive model and its application to multimedia design," Electronics & Telecommunications Research Institute, Daejeon, Korea, October 2006.

2. Invited Seminar, "Reactive information displays: Theory and applications," Electronics & Telecommunications Research Institute, Daejeon, Korea, October 2006.

3. Paper Presentation, "Exploring the effect of animation and progressive revealing on diagrammatic problem solving," Fourth International Conference on the Theory and Application of Diagrams, Stanford University, June 2006.

4. Paper Presentation, "Contextualizing learning about complex systems from visualizations: cognitive theory, empirical evidence and design guidelines", Annual Meeting of the American Educational Research Association (AERA), Montreal, Canada, April 2005.

5. Research Seminar, "Causal learning about complex systems," Florida Institute for Human and Machine Cognition, Pensacola, FL, March 2005.

6. Paper Presentation, "Reactive information displays: A progress report," Office of Naval Research Workshop on Attention, Perception and Modeling for Complex Displays, Naval Undersea Warfare Center Division, Newport, RI, May 2004.

7. Paper Presentation, "Mental imagery in problem solving: An eye tracking study," Third ACM Symposium on Eye Tracking Research & Applications, San Antonio, TX, March 2004.

8. Paper Presentation, "Predictors of success in diagrammatic problem solving," Third International Conference on the Theory and Application of Diagrams, Cambridge, UK, March 2004.

9. Paper Presentation, "Reactive information displays," INTERACT 2003: Ninth IFIP TC 13 International Conference on Human-Computer Interaction, Zurich, Switzerland, September 2003.

10. Paper Presentation, "Reactive information displays," Office of Naval Research Workshop on Attention, Perception and Data Visualization, Rensselaer Polytechnic Institute, Troy, NY, June 2003.

14. Related Projects and Grants

11. Learning about causal systems in complex domains: A multidisciplinary synthesis of the state-of-the-art and research challenges, 2003-2007, National Science Foundation, SBE0350342.

1. Analysis and Synthesis of Hypermedia Information Visualizations, 1999-2002, Office of Naval Research, N000149611187.

2. Participant Support for Second International Conference on Theory and Application of Diagrams, 2002, Office of Naval Research; N000140210350.

3. Eye Tracking Equipment for Analysis and Synthesis of Human Interactions with Hypermedia

Information Visualizations, 2000-2001, Defense Universities Research Instrumentation Program (DURIP) administered through Office of Naval Research, N000140010418.

4. Equipment for Eye Tracking, 1996, this equipment was provided to Auburn University by Carnegie-Mellon University through an ONR-managed research equipment grant with PI John Anderson, Department of Psychology, Carnegie Mellon University.